Computer-Simulation Movie
of Ionospheric Electric Fields and Currents
for a Magnetospheric Substorm Life Cycle

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Numerical solution of the current conservation equation gives the distributions of electric fields and currents in the global ionosphere produced by the field-aligned currents (Kamide and Matsushita, 1979a, b). By altering ionospheric conductivity distributions as well as the field-aligned current densities and configurations to simulate a magnetospheric substorm life cycle, which is assumed to last for five hours, various patterns of electric fields and currents are computed for every 30-second interval in the life cycle.

The simulated results are compiled in the form of a color movie, where variations of electric equi-potential curves are the first sequence, electric current-vector changes are the second, and fluctuations of the electric current system are the third. The movie compresses real time by a factor of 1/180, taking 1.7 minutes of running time for one sequence. One of the most striking features of this simulation is the clear demonstration of rapid and large scale interactions between the auroral zone and middle-low latitudes during the substorm sequences.

This technical note provides an outline of the numerical scheme and worldwide contour maps of the electric potential, ionospheric current vectors, and the equivalent ionospheric current system at 5-minute intervals as an aid in viewing the movie and to further detailed study of the 'model' substorms. These plots are excerpts from the larger data set, plotted for every 30 seconds, which were used to generate the motion pictures. The 16 mm color movie may be available at a price currently quoted: requests should be addressed to Matsushita.

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1. INTRODUCTION

We have developed an algorithm to derive the horizontal electric fields and currents in the global ionosphere produced by field-aligned currents (Kamide and Matsushita, 1979a). The steady state equations for current conservation have been solved numerically by assuming (1) several divided regions of the global earth (such as the polar cap, auroral region, and middle and low latitudes), (2) the anisotropic electric conductivities for each region with a relatively continuous change at the boundaries of the regions, and (3) downward and upward field-aligned current intensities in the auroral region. These assumptions are based on our current knowledge of auroral phenomena and geomagnetic variations as well as rocket and satellite measurements of field-aligned currents and radar measurements of the ionospheric conductivities. Resultant computer-plotted diagrams include equipotential contour maps of the electric fields, vector distributions of the electric fields and currents, and electric current patterns equivalent to the magnetic field effect produced by the field-aligned and actual ionospheric currents.

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One of the merits of this method is that it is possible to examine, in quantitative detail, how conductivity enhancement and field-aligned currents in auroral latitudes affect the global potential distribution, which is responsible for the ionospheric current flow. By comparing these results with some of the recent relevant observations, Kamide and Matsushita (1979a, b) have demonstrated the accuracy of the basic assumptions leading to the main features observed during both quiet and disturbed periods. Similar "steady-state simulation" studies have successively been made by Lyatsky et al. (1974), Yasuhara et al. (1975), Maekawa and Maeda (1978), Nisbet et al. (1978), and Nopper and Carovillano (1978) for average conditions of geomagnetic activity.

It may be interesting in this respect to extend such a numerical scheme to a system in which variable aspects of magnetospheric substorms are included. In this way we may be able to isolate certain parameters of the system which can reproduce the field and current patterns changing in succession before, during, and after substorms.

When the driving electromagnetic field changes with time during substorm processes, one of the time scales of the ionosphere-magnetosphere system we must consider is the induction time constant of the ionosphere. For sufficiently large horizontal electric field perturbations, the response time of the entire ionosphere is on the order of seconds (Vasyliunas, 1972). In contrast, a nonvanishing divergence of the ring current plays an important role in the production mechanism of field-aligned currents. Consideration of the global magnetospheric convection indicates that the time scale for relaxation of the magnetospheric plasma including the ring current to a new equilibrium distribution is on the order of hours. Thus, we expect that the ionospheric electric fields and currents can be obtained to a good approximation by modeling the substorm as a sequence of steady states, for which the distribution and intensity of the field-
aligned currents is assumed at each time step, as well as ionospheric conductivity distribution.

Extensive computer simulations are conducted in which the time-dependent character of the substorms is assumed as a sequence of steady states, where realistic field-aligned currents and conductivities are employed at each time interval. We choose a 5-hr interval for the simulation studies in which two substorm activities are assumed to occur sequentially. The results of the simulations are compiled in the form of a 16-mm color movie of about 5-min long. This technical note provides worldwide contour maps of the electric potential, ionospheric current vectors, and the equivalent ionospheric current system at 5-min intervals as an aid in viewing the movie and to further detailed study of the 'model' (or 'artificial') substorms. These plots are excerpts from the larger data set, plotted for every 30 seconds, which were used to generate the motion pictures.

2. OUTLINE OF NUMERICAL SCHEME

A detailed description of the basic equations governing the simulation scheme has been given by Kamide and Matsushita (1979a), and similar treatments have recently been conducted by Nisbet et al. (1978) and Nopper and Carovillano (1978), but a brief outline is presented here for the readers' convenience.

The current continuity equation in a steady state is written as

\[ \text{div} \mathbf{j} = -\text{div}(\mathbf{a} \cdot \text{grad}\phi) = j_\parallel \sin \chi \]

where \( \mathbf{j} \) is the ionospheric height-integrated current density, \( \mathbf{a} \) is the dyadic of the height-integrated ionospheric conductivity, \( \phi \) is the electric potential in which the electric field \( \mathbf{E} \) is given by \( -\text{grad}\phi \), \( j_\parallel \) is the density of the field-aligned current (positive for...
a downward and negative for an upward current), and \( \chi \) is the inclination
angle of a geomagnetic field line with respect to the horizontal ionosphere.
Given suitable boundary conditions, the electric potential can be obtained
numerically for the given distribution of the ionospheric conductivities
and the field-aligned currents by solving the following two-dimensional,
second-order differential equation:

\[
A \frac{\partial^2 \phi}{\partial \theta^2} + B \frac{\partial \phi}{\partial \theta} + C \frac{\partial^2 \phi}{\partial \lambda^2} + D \frac{\partial \phi}{\partial \lambda} = F
\]

where

\[
A = \sin^2 \theta \Sigma_{\theta \theta} \\
B = \sin \theta \left[ \frac{\partial}{\partial \theta} \left( \sin \theta \Sigma_{\theta \theta} \right) - \frac{\partial \Sigma_{\theta \lambda}}{\partial \lambda} \right] \\
C = \Sigma_{\lambda \lambda} \\
D = \sin \theta \frac{\partial \Sigma_{\theta \lambda}}{\partial \theta} + \frac{\partial \Sigma_{\lambda \lambda}}{\partial \lambda} \\
F = -a^2 j_\parallel \sin^2 \theta \sin \chi
\]

and \( a \) is the radius of the current sheet of the ionosphere. Here, the
usual \((\theta, \lambda)\) polar coordinate system is used, in which \( \theta \) is colatitude and
\( \lambda \) is longitude measured eastward from midnight.

We are then able to obtain the electric field \( E(E_\theta, E_\lambda) \) from

\[
E_\theta = -\frac{\partial \phi}{\partial \theta} \\
E_\lambda = -\frac{\partial \phi}{a \sin \theta \partial \lambda}
\]

By using the assumed height-integrated conductivities \( \Sigma \) and the computed
electric field, the ionospheric current can be deduced from

\[
\begin{bmatrix}
i_\theta \\
i_\lambda
\end{bmatrix} = \begin{bmatrix}
\Sigma_{\theta \theta} & \Sigma_{\theta \lambda} \\
-\Sigma_{\theta \lambda} & \Sigma_{\lambda \lambda}
\end{bmatrix} \begin{bmatrix}
E_\theta \\
E_\lambda
\end{bmatrix}
\]
It is also possible to generate the equivalent ionospheric current system from the assumed field-aligned currents and calculated ionospheric currents. The equivalent ionospheric currents can then be directly compared with ground magnetic observations.

In the following calculations we simulate a substorm sequence by changing the distribution of both the field-aligned currents and the ionospheric conductivities with time.

2.1. Field-Aligned Currents

Based on recent satellite observations (e.g., Iijima and Potemra, 1976a, b), the main characteristics of the current flow during disturbed periods are summarized as follows: (1) The field-aligned currents are confined to the region of the auroral oval. (2) In the morning sector, there are downward currents in the poleward half of the auroral oval and upward currents in the equatorward half; the current direction is reversed in the evening sector. (3) The intensities of the total amount of the upward and downward currents are in general not equal, so that there is a net field-aligned current flowing into or away from the ionosphere depending on local time.

To characterize these recent observations, we assume that the distribution functions of the field-aligned current density are

\[
\begin{align*}
  j_{\parallel P} &= \pm \int j_{\parallel o} \exp \left( -\frac{(\theta - \theta_o P)^2}{(D_\theta P)^2} - \frac{(\lambda + \lambda_o P)^2}{(D_\lambda P)^2} \right) \\
  j_{\parallel E} &= \mp \int j_{\parallel o} \exp \left( -\frac{(\theta - \theta_o E)^2}{(D_\theta E)^2} - \frac{(\lambda + \lambda_o E)^2}{(D_\lambda E)^2} \right)
\end{align*}
\]

where \( P \) and \( E \) stand for the poleward and equatorward portions of the field-aligned currents, respectively, and the upper or lower sign is taken for...
positive or negative value of \( \lambda \). A sketch of the configuration of the model is shown in Figure 1. The maximum field-aligned current density \( j_{||0}^{P,E} \) is assumed to occur at the colatitude \( \theta_0^{P,E} \) and the longitude \( \lambda_0^{P,E} \), and the Gaussian distributions are specified by \( D_\theta^{P,E} \) and \( D_\lambda^{P,E} \), which are chosen in such a way that the intensity of \( j_{||} \) becomes approximately 0.2 \( j_{||0} \) at the boundaries of the auroral enhancement belt. The total field-aligned current is calculated as

\[
I_{||}^{P,E} = \int \int j_{||}^{P,E} a^2 \sin \theta \, d\theta \, d\lambda
\]

2.2. Ionospheric Conductivities

The ionospheric conductivity model has essentially two components: one is of dayside origin and the other represents an enhancement along the nightside auroral belt due to substorm-associated particle bombardment.

The conductivity originating in the dayside adopted here is a fairly realistic distribution of the height-integrated conductivity developed by Tarpley (1970) and improved by Richmond et al. (1976) and Richmond (personal communication, 1979). The height-integrated conductivities are written as

\[
\Sigma_{\lambda \lambda} (\theta, \lambda) = \Sigma_1^*(\theta) \sin \chi f (\cos K)
\]

\[
\Sigma_{\theta \theta} (\theta, \lambda) = \Sigma_1^*(\theta)/\sin \chi f (\cos K)
\]

\[
\Sigma_{\theta \lambda} (\theta, \lambda) = \Sigma_2^*(\theta) f (\cos K)
\]

where \( \Sigma_1^* \) and \( \Sigma_2^* \) are the magnetic-field-integrated Pedersen and Hall conductivities for an overhead sun and \( f(\cos K) \) is a function describing the decrease of height-integrated conductivity with increasing solar zenith angle \( K \). The solar zenith angle \( K \) is determined from the coordinates \( (\theta, \lambda) \) by
Fig. 1. Schematic diagram to show the field-aligned currents $j_y$ and auroral regions I, II, III, and IV with different amounts of electric conductivities.

Fig. 2. Height-integrated conductivity distributions along the noon-midnight meridian in the equinoctial season.

Fig. 2. Height-integrated conductivity distributions along the noon-midnight meridian in the equinoctial season.
\[
\cos K = \cos \theta \cos \theta_s + \sin \theta \sin \theta_s \cos (\lambda - \lambda_s)
\]

where \((\theta_s, \lambda_s)\) gives the subsolar point coordinates. Figure 2 shows the distribution of \(\Sigma_{\theta \theta}, \Sigma_{\lambda \lambda},\) and \(\Sigma_{\theta \lambda}\) along noon \((\lambda = 180^\circ)\) and midnight \((\lambda = 0^\circ)\) meridians for \(\theta_s = 90^\circ\) and \(\lambda_s = 180^\circ\) representing equinoctial conditions.

It is important to note that we cannot give the nightside origin conductivity independent of the distribution of the field-aligned currents. We assume in this simulation study the conductivity distribution in the night sector based primarily on recent Chatanika radar observations of the conductivity to be functions of local time and substorm activity (e.g., Banks and Doupnik, 1975; Horwitz et al., 1978) and also on auroral observations with respect to the location of the field-aligned currents (e.g., Kamide and Rostoker, 1977). In particular, the recent simultaneous observations of large-scale auroras and the field-aligned currents have indicated that there are at least four different regions with different auroral luminosities corresponding to the different directions of the field-aligned currents. We therefore take into account four conductive regions in our model. As shown in Figure 1, we divide the entire conductive area into the following four regions: Regions I, II, III, and IV. The poleward half of the auroral belt corresponds to Regions I and II, with Region I located in the morning sector and Region II located in the evening sector, where discrete auroras are generally observed. We expect that Region II is the most conductive region during substorms. In the equatorward half of the auroral belt, Regions III and IV represent the morning and evening sectors, respectively. Region IV corresponds to the diffuse auroral region in the evening sector.

In each of the four regions, the height-integrated conductivities are assumed to have Gaussian functions given by
\[ \Sigma_{\Theta \lambda}^i = \Sigma_{2m}^i \exp \left( -\frac{(\theta - \theta'_o)^2}{(\Delta \theta)^2} - \frac{(\lambda - \lambda'_o)^2}{(\Delta \lambda)^2} \right) \]
\[ \Sigma_{\Theta \Theta}^i = \frac{1}{2} \Sigma_{\Theta \lambda}^i \sin \chi \]
\[ \Sigma_{\lambda \lambda}^i = \frac{1}{2} \Sigma_{\Theta \lambda}^i \sin \chi \]

where \( i = I, II, III, \) and IV, and \((\theta'_o, \lambda'_o)\) is the center location of each region at which the conductivity \( \Sigma_{\Theta \lambda}^i \) is maximum \( (= \Sigma_{2m}^i) \). \( \Delta \theta \) and \( \Delta \lambda \) are taken in such a way that \( \Sigma_{\Theta \lambda}^i \) becomes approximately 0.2 \( \Sigma_{2m}^i \) at the boundaries of the auroral enhancement. Note that since the auroral enhancement is given only in high latitudes where \( \sin \chi \approx 1 \), we use hereinafter the term Pedersen \( \Sigma_p \) and Hall \( \Sigma_H \) conductivities to represent auroral-belt \( \Sigma_{\Theta \Theta} (\approx \Sigma_{\lambda \lambda}) \) and \( \Sigma_{\Theta \lambda} \), respectively.

3. SIMULATION PARAMETERS

Figure 3 shows variations of several parameters of the field-aligned currents and the ionospheric conductivities which are assumed to represent a typical sequence of substorm life cycle. A 5-hr interval \( (T = 0 \text{ through } T = 300 \text{ min}) \) is simulated in which two substorms are assumed to occur. The first substorm is believed to represent a typical substorm. We mean by 'typical' to attempt to model medium-sized, isolated substorms which are perhaps associated with the southward turning of the interplanetary magnetic field (IMF). A possible scenario is that the IMF is directed northward with large magnitude (say, > 5 nT) for at least several hours before \( T = 0 \), and that after \( T = 0 \), the IMF stays southward until \( T = 60 \text{ min} \) which is the onset time of the first substorm.

The total field-aligned current intensities just before \( T = 60 \text{ min} \) in the poleward half and in the equatorward half of the auroral belt are 1 x
Fig. 3. Variations of several parameters concerning field-aligned electric currents and Hall and Pedersen integrated conductivities assumed for the five hour substorm time span.
$10^5$ and $0.25 \times 10^5$ A, respectively (see the top panel of Figure 3). The centers of the field-aligned currents are initially located at $\chi_{O}^{P,E} = \pm 90^\circ$ at $T = 0$ and gradually approach midnight (see the third panel). In the fourth panel, variations of the latitudinal width of the assumed auroral belt are shown in terms of $\theta_{PB}$ and $\theta_{EB}$, which denote respectively the poleward and equatorward boundaries of the auroral enhancement. Based on recent suggestions (e.g., Akasofu, 1975), we assume that the polar cap responds to the southward IMF by increasing its size from $\theta_{PB} = 15^\circ$ (at $T = 0$) to $\theta_{PB} = 23^\circ$ (at $T = 60$ min). The enhancement of the ionospheric conductivities, as well as the $\Sigma_{H}/\Sigma_{P}$ ratio, is also assumed to increase slowly preceding the first substorm in Regions II and III, where electron auroras are generally observed in association with the upward field-aligned currents. These features are displayed in the bottom two panels of Figure 3.

The onset of the first substorm is characterized by a sudden increase in the field-aligned current strength, the expansion of the auroral belt both in the poleward and equatorward directions, and the enhancement of ionospheric conductivity together with an increase of the Hall to Pedersen conductivity ratio in Region II, where the most dramatic auroral features, such as the westward traveling surge, develop in the expansion phase of substorms. The field-aligned currents in the poleward half reach their maximum ($I_{||}^{P} = 2 \times 10^6$ A) at $T = 90$ min, 30 min after the onset, in contrast to the maximum value for $I_{||}^{E} ( = 1 \times 10^6$ A) in the equatorward half. At the maximum epoch of the substorm, the latitudinal width of the auroral belt amounts to $11^\circ$. The equatorward half field-aligned current intensities $I_{||}^{E}$ are assumed to continue increasing even after $T = 90$ min, reaching eventually $1.2 \times 10^6$ A at $T = 120$ min when the poleward-half field-aligned current intensities $I_{||}^{P}$ are decreasing (see the top panel).

The conductivity in Region IV is assumed to behave in the same way as $I_{||}^{E}$; $\Sigma_{P}^{IV}$ and $\Sigma_{H}^{IV}$ increase until $T=120$ min. These assumptions are made based
on the observation that the field-aligned currents in the equatorward half are connected to the partial ring current in the magnetosphere, which generally develops several to several tens of minutes later than the midnight westward electrojet. Finally by the time $T=180$ min, the first substorm is practically over, but the ionospheric conductivities continue to decrease even during the period $T=180-240$ min.

The second substorm starts at $T=240$ min. By this model substorm, we attempt to simulate the so-called 'contracted-oval' or weak substorms, which occur in higher latitudes with smaller auroral and electrojet energy, compared to the corresponding quantities associated with 'normal' substorms. The lifetime is taken to be 1 hr for this second substorm. We assume smaller field-aligned currents, particularly in the equatorward half of the auroral region, and smaller conductivities than those for the first substorm. Note, however, that this does not mean that the current density is small as well. In fact, the maximum current density is almost comparable to that of the first substorm just after the onsets (see the second panel in Figure 3), indicating that the second substorm is localized in both latitude and longitude. We suggest that the second substorm would correspond to a period of the northward IMF (Lui et al., 1976), following a southward IMF related to the first substorm. Note that Kamide and Matsushita proposed a phenomenological model of substorm time sequences where such a weak substorm tends to occur when the IMF turns northward but the magnetosphere still has available substorm energy.

4. MOVIE FILM

Assuming the time change in the distribution of the field-aligned currents and the ionospheric conductivities as described in the previous section, the electric potential, the ionospheric currents, and equivalent ionospheric current functions are calculated. A comparison of these
patterns with recent relevant observations indicates that the simulation results can reproduce quite well a variety of quiet-time and substorm-time features of the electric fields and currents in the ionosphere. To see further how these quantities change progressively, the world patterns are plotted on a 16 mm color movie film for each 30 sec of the entire 5-hr time span. Each film frame includes also the maximum electrojet intensity for the entire interval (westward electrojet toward the left and eastward electrojet toward the right separately by green color) as well as the assumed field-aligned current intensity ($I_{||}^P$ toward the left and $I_{||}^E$ toward the right separately by red color).

We note that it is neither our intention to present where the assumed field-aligned currents originate nor how they are closed in the magnetosphere. We also neglect the effects of the ring, tail, and magnetopause currents in obtaining the equivalent current vectors. The equatorial electrojet in the dayside ionosphere cannot be reproduced as well, because of the two-dimensional treatment of the ionosphere. Thus, our calculations for the ionospheric currents are not very accurate in low latitudes, particularly below 10°, and those for the equivalent current system are inaccurate in middle and low latitudes where the magnetospheric currents are the major source of ground magnetic perturbations.

The movie film consists of three successive sequences: The first sequence shows the electric potential contours, the second sequence includes the ionospheric current vectors, and the last one presents the equivalent ionospheric current system. Different parameters are represented by different colors: the electric potential contours and the equivalent current systems are shown by light blue, eastward and westward current vectors are shown respectively by green and red, and latitudinal circles (00, 30, and 60° N) as well as noon-midnight and dawn-dusk meridians are represented by light yellow. Each frame is repeated four times, allowing the viewer to follow
properly the progression of the corresponding time changes. Each sequence consists of 2404 movie frames for the entire 5-hr simulation time, requiring about 1.7 min projection time.

There are several important problems which can be studied in detail by the careful examination of changes in the world patterns of the electric fields and currents as the frames proceed. Among them, the followings are particularly interesting:

1. Penetration of substorm electric field into low latitudes.

A topic of recent observational and theoretical interest is the extent to which ionospheric electric fields originating in high latitudes during substorms penetrate the middle and low latitude ionosphere. By combining available observations of low-latitude electric fields by various techniques, it may well be said that it is certainly possible for the high-latitude origin fields to be carried deep into middle and low latitudes, but this does not always occur systematically during substorm activity (e.g., Blanc, 1978). Some complicated processes seem to regulate the efficiency of the penetration. Recent theoretical studies (e.g., Swift, 1971; Vasyliunas, 1972; Jaggi and Wolf, 1973; Harel and Wolf, 1976) suggest that the relative strength of the upward and downward field-aligned currents at a given local time determines how rapidly the electric field is shielded in the subauroral zone. In the magnetosphere, the Alfven layer tends to reduce the magnitude of the convection electric field in the inner magnetosphere. However, this shielding effect could be reduced significantly if the ionospheric conductivity in the auroral belt is large. By checking frame by frame of the movie, we may be able to find the relative importance of the time changes in the ionospheric conductivity and field-aligned currents which are responsible for the efficiency of the field penetration. A preliminary examination of the world potential contours indicates that there seems to be an asymmetry in the penetration of the electric field into low latitudes.
between morning and evening hours. That is, the electric field originating in auroral latitudes tends to decay more rapidly in the evening sector than in the morning sector. Details will be discussed elsewhere (Kamide and Matsushita, 1981).

2 - Expansion of the auroral electrojets.

In the simulation movie, we have modeled the growth of the substorms by assuming an increase of the size of the auroral belt where the ionospheric conductivity and field-aligned currents are enhanced significantly. The increase is accomplished by the expansion of the area in both latitudinal and longitudinal directions. Although there is no doubt that such an assumption makes the auroral electrojet area expand generally as a whole, it is interesting to examine the response of the eastward and westward electrojets separately to the expansion of the auroral belt. What happens to the electrojets near midnight is an important question as well. Kamide and Matsushita (1979b) have indicated that there can be two elements of the westward electrojets: one is seen primarily in the premidnight sector and is produced mainly by the enhancement of the ionospheric conductivity, and the other tends to appear in the morning sector where the electric field is responsible for the electrojet. Our particular concern then lies in seeing how differently these two types of the ionospheric currents develop in conjunction with the progress of substorms.

3 - Dynamic behaviour of the Harang discontinuity.

The Harang discontinuity is defined by the transition of either the north-south electric fields or the east-west electrojets. Recently, many works have suggested the role of the Harang discontinuity in the generation and the intensification of substorms (e.g., Rostoker et al., 1980; Baumjohann et al., 1980). In the electric potential contours, it may not be easy to delineate the discontinuity which can be defined only be the north-south electric fields. The contour lines themselves are not discontinuous, but
only show some deformation near the Harang discontinuity. In the movie film, the eastward and westward electrojets are represented by different colors, so that it is easy to follow dynamical behaviour of the two-dimensional boundary of these currents.


The equivalent ionospheric current system can be directly compared with the distribution of ground magnetic perturbations. Recently, several computer techniques have successively developed to plot magnetic potential contours for the ground magnetic perturbation vectors, from which the equivalent current system is deduced. These have made it possible to illustrate the progressive change of the equivalent current pattern during the course of substorms (Boström, 1971; Kamide et al., 1976; Richmond et al., 1979). Comparing the two-dimensional equivalent current systems obtained from ground observations alone with those seen in the movie frames, the three-dimensional current system can roughly be estimated. Also, space-time changes of the ionospheric conductivity and field-aligned currents may be deduced.

5. THE 5-MIN PLOTS

The electric potential (left), the ionospheric current vectors (center), and the equivalent ionospheric current system (right) are shown in Figure 4 for every 5 minutes with the maximum intensities of the eastward and westward auroral electrojets (AE in A/m) and the assumed field-aligned current intensities (FAC in $10^6$ A) for the entire 5-hr interval. Note that the maximum electrojet intensities are similar to the AU and AL magnetic activity indices. Time interval is identified along the lefthand edge, 60 minutes per tick mark. The frame time is denoted by the time marking bar which moves from top to bottom of these curves as time increases. Exact time (like $T = 90.0$ min), vector scale, contour interval, latitude and local
time are identified for each diagram. For the disturbed period during the maximum epoch of the first substorm, smaller contour intervals are used for the potential and equivalent current functions, and smaller scales are employed for the current vectors. (In the movie these values are not changed throughout the entire interval for the viewers' convenience.)

We discuss briefly some aspects of progressive changes in the potential contours, the ionospheric current vectors including the auroral electrojets, and the equivalent current patterns. Before the first substorm onset (T = 60 min), the potential distribution consists of two main vortices in high latitudes: high potential contour in the morning sector and low in the evening sector. Starting at T = 25 min, the contour line begins to be deformed near midnight, a result of the increase of the ionospheric conductivity in the midnight auroral belt. By approximately T = 45 min, this deformation shows apparent kinks which extend to earlier and later local times. The ionospheric current distribution is not particularly exciting before the onset, except that current vectors in the auroral belt gradually increase. It is noticeable in the equivalent current system that the size of the counterclockwise vortex in the evening sector is larger than that of the clockwise vortex, and that the flow line is not directed exactly from midnight to noon but from premidnight to prenoon. Due to the assumption of the gradual increase in the Hall-to-Pedersen conductivity ratio in the auroral belt, the direction of the flow lines in the polar cap indicates clockwise rotation with time.

At T = 60 min (onset time of the first substorm), the electric field appears to be reversed temporarily. This is apparently produced by the corresponding reversal of the net field-aligned currents. That is, the initial substorm signature is assumed to start in a narrow area near midnight where an element of the three-dimensional current circuit is given in a way discussed by Rostoker (1974). Although the element has a normal
current direction in the poleward half of the auroral belt, viz, downward in the postmidnight and upward in the premidnight sectors, the total current of this circuit is small compared with that of the field-aligned current system in the equatorward half. Corresponding to this, the auroral electrojets in the midnight sector are very complicated, including the appearance of the intense, localized eastward current near midnight.

After the onset, the number of the electric potential contour lines increases, indicating the increase of the electric field strength. In the early expansion phase (T = 65 to 75 min), the potential pattern is complicated and localized in and near the auroral belt. However, during the maximum epoch of the first substorm, the contour lines expand to both higher and lower latitudes. This penetration of the electric field is reduced after T = 90 min, particularly in the evening sector, which is perhaps produced by the combination of the decrease and increase of the field-aligned currents in the poleward half and equatorward half, respectively, of the auroral belt. The westward electrojet seems to intrude well in earlier local times, tending toward the higher latitudes of the eastward electrojet region in the evening sector.

As seen in the plotted variation of the maximum ionospheric currents (see AE in each diagram), the electrojet intensities during the first substorm show relatively complicated time changes which can be compared with simple, linearly-changing field-aligned currents. This implies that some combination of the upward and downward field-aligned current intensities and the conductivity values is responsible for the efficiency of the growth of the auroral electrojets and the current closure in the ionosphere. Note that only the east-west component of the ionospheric currents contributes to the auroral electrojets plotted in this diagram.

Near T = 120 min, when the equatorward half field-aligned currents reach the maximum intensity, the potential contours again become complicated.
In nightside low latitudes, the direction of the electric field changes according to local time and temporal variations of the ionospheric conductivities, although the field direction does not seem to change drastically in the polar cap. During the recovery phase after \( T = 140 \) min, the potential distribution is similar to the earlier quiet time pattern in the sense that it consists of two vortices, except that the field is still enhanced compared to quiet times. In addition, note that the eastward electrojet is increasing its intensity in association with the increase of the downward field-aligned current in the evening sector, while the westward electrojet is rapidly decreasing.

The second substorm starts with the sudden increase of the westward electric field near midnight; see the potential contour at \( T = 245 \) min. Throughout the interval of the second substorm, the overall potential pattern appears to be simple and unchanged. It consists of essentially twin vortices, one on the morning side and the other on the evening side, both of which are close to midnight. It is interesting to note that the westward electrojet is localized within a few degrees in latitudes near midnight, during the second substorm, and that the eastward electrojet is very weak (see AE values).

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REFERENCES


Fig. 4. Simulated electric field and current distributions in the northern hemisphere.
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